



Uncovering Multiple Mechanisms of of $\beta\beta0\nu$ decay

TAUP 2013

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Based on:

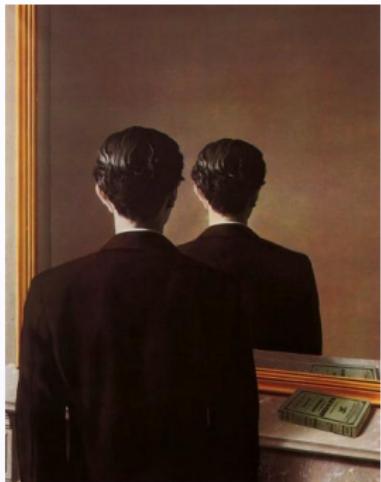
A. Faessler, A. M., S.T. Petcov, F. Simkovic, J. Vergados,
Phys. Rev. D83(2011)113003 &
A. M., S.T. Petcov, F. Simkovic, JHEP02(2013)025

$\beta\beta0\nu$ Decay

Majorana nature $\rightarrow \beta\beta0\nu$: $(A, Z) \rightarrow (A, Z + 2) + 2e^-$

- Process forbidden in the SM
- Lepton number is not conserved $\Delta L = \pm 2$
- Possible if neutrinos are Majorana type
- Standard $\beta\beta0\nu$ -decay amplitude is function of the effective Majorana mass parameter

$$|\langle m \rangle| = \left| \sum_j^{\text{light}} (U_{ej}^{PMNS})^2 m_j \right|, \quad m_j < 1\text{eV}$$

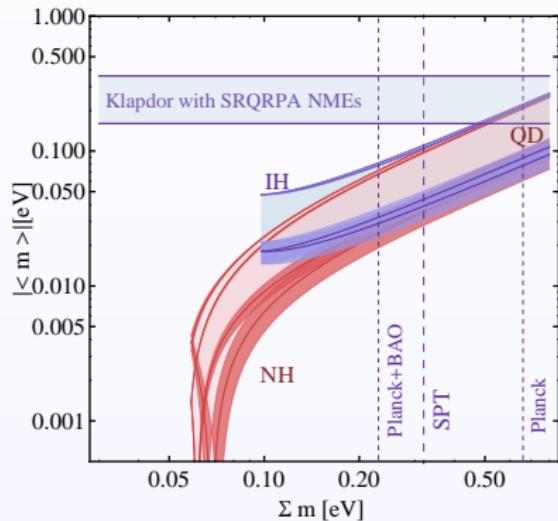
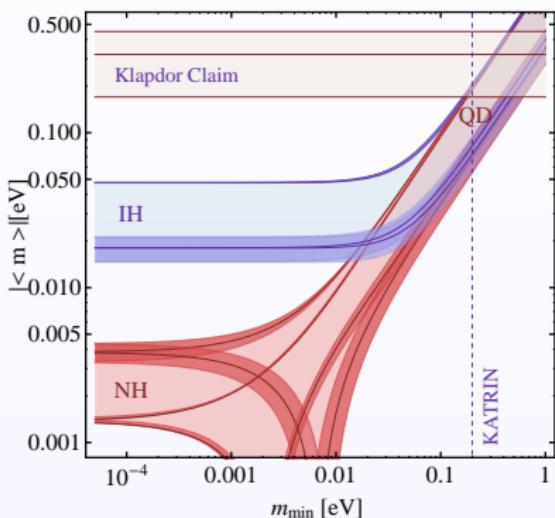


René Magritte, *Portrait of Edward James*.

$\beta\beta0\nu$ -Decay: Majorana effective mass

Standard $\beta\beta0\nu$ -decay amplitude is function of the effective Majorana mass parameter

$$|\langle m \rangle| = \left| \sum_j^{\text{light}} (U_{ej}^{PMNS})^2 m_j \right|, \quad m_j < 1 \text{ eV}$$



Plots obtained using 2σ uncertainty in the oscillation parameters.

Multiple mechanisms

If $\beta\beta0\nu$ decay will be **observed**, the question will inevitably arise:

Which mechanism is triggering the decay?
How many mechanisms are involved?

A number of different mechanisms is possible:

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(E, Z) \left| \sum_i \eta_i^{LNV} M_i^{0\nu} \right|^2$$

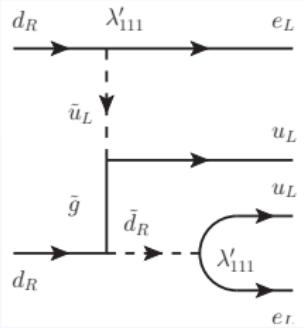
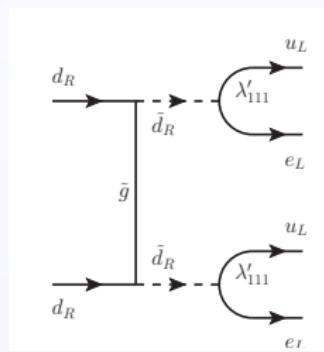
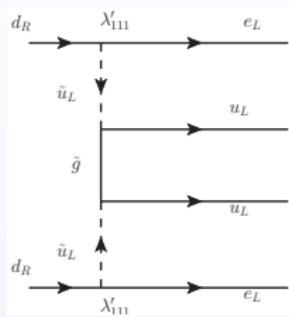
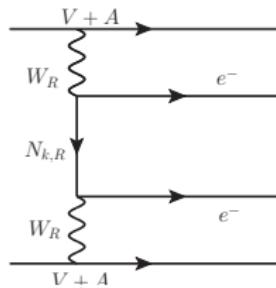
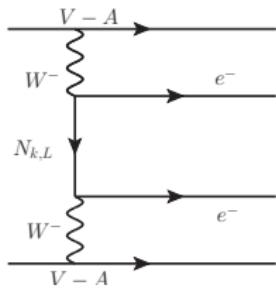
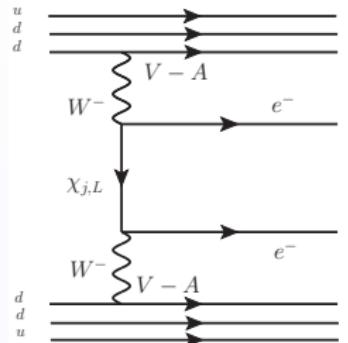
These mechanisms might trigger $\beta\beta0\nu$ -decay **individually or together and can interfere or not.**

- η_i^{LNV} is the fundamental LNV parameter characterizing the mechanism *i*. η_i^{LNV} can be **real or complex** → CPV.
- $G^{0\nu}(E, Z)$ is the phase space factor
- $M_i^{0\nu}$ is the nuclear matrix element (NME)

$\beta\beta0\nu$ decay is allowed by a number of different models: Left-Right Symmetry, R parity violating SUSY...

Possible Mechanisms

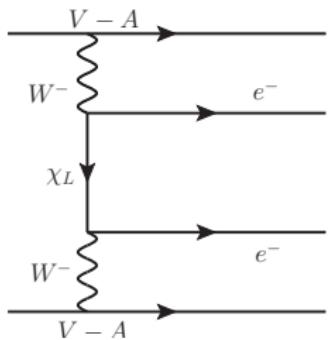
Standard, Heavy Neutrino exchange, SUSY particles...



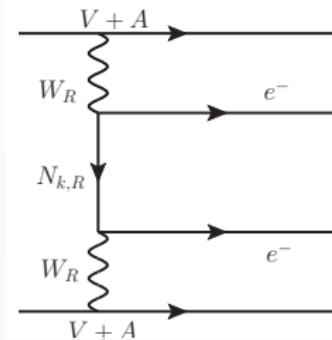
Multiple mechanisms: Two **Not** interfering mechanisms Analysis

Example

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(E, Z) \left| \sum_i \eta_i^{LNV} M_i^{0\nu} \right|^2$$



$$\text{amplitude} \propto \eta_\nu [\bar{e}(1 + \gamma_5)e^c]$$



$$\text{amplitude} \propto \eta_N^R [\bar{e}(1 - \gamma_5)e^c]$$

Multiple mechanisms: Two **Not** interfering mechanisms Analysis

Example

Example. We assume light LH and heavy RH Majorana neutrino exchanges \rightarrow LNV fundamental parameters $|\eta_\nu|$ and $|\eta_R|$

$$\begin{cases} \frac{1}{T_1 G_1} = |\eta_\nu|^2 |M'^{0\nu}_{1,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{1,N}|^2, \\ \frac{1}{T_2 G_2} = |\eta_\nu|^2 |M'^{0\nu}_{2,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{2,N}|^2 \end{cases}$$

Positivity Conditions:

$$|\eta_\nu|^2 > 0$$

$$|\eta_R|^2 > 0$$

$|\eta_\nu|^2, |\eta_R|^2 > 0$ ($A_1 < A_2$) only if:

$$\frac{T_1 G_1 |M'^{0\nu}_{1,N}|^2}{G_2 |M'^{0\nu}_{2,N}|^2} \leq T_2 \leq \frac{T_1 G_1 |M'^{0\nu}_{1,\nu}|^2}{G_2 |M'^{0\nu}_{2,\nu}|^2},$$

If one of the two solutions is zero then **only one mechanism is active**.

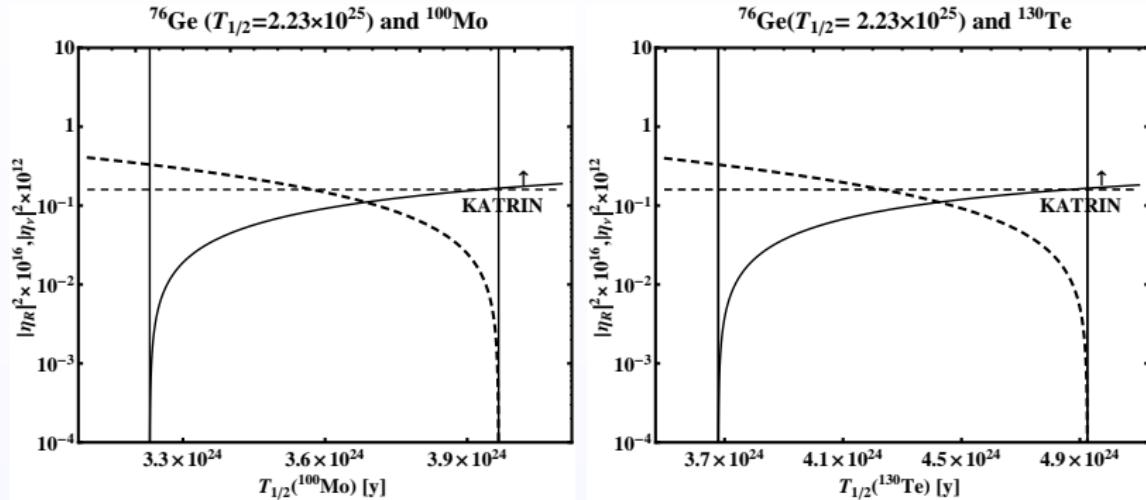
Using the values “CD-Bonn, large, $g_A = 1.25$ ”, we get the positivity conditions:

$$0.15 \leq \frac{T_{1/2}^{0\nu}({}^{100}\text{Mo})}{T_{1/2}^{0\nu}({}^{76}\text{Ge})} \leq 0.18 \quad , \quad 0.17 \leq \frac{T_{1/2}^{0\nu}({}^{130}\text{Te})}{T_{1/2}^{0\nu}({}^{76}\text{Ge})} \leq 0.22$$

Very narrow intervals!

Two not interfering mechanisms

Results

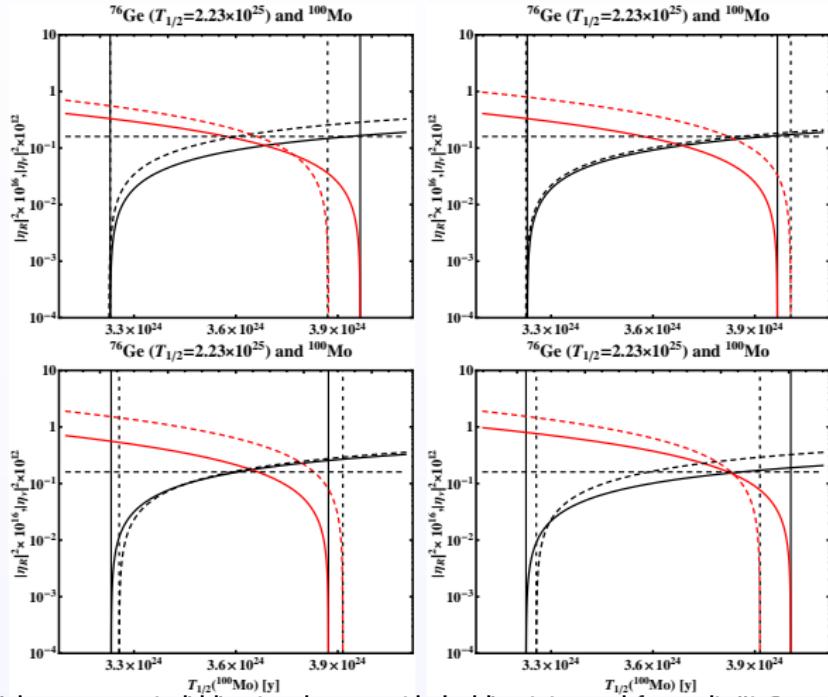


The values of the rescaled parameters $|\eta_\nu|^2$ (solid line) and $|\eta_R|^2$ (dashed line), for $T_{1/2}^{0\nu}(^{76}\text{Ge})$ and $T_{1/2}^{0\nu}(^{100}\text{Mo})$ - ($T_{1/2}^{0\nu}(^{76}\text{Ge})$ and $T_{1/2}^{0\nu}(^{100}\text{Te})$) - lying in a specific interval. The physical (positive) solutions are delimited by the two vertical lines. The horizontal dashed line corresponds to the prospective upper limit from the upcoming ${}^3\text{H}$ β -decay experiment KATRIN.

Dependence on g_A and on the NMEs

Results: change smaller than 10%

NMEs computed within the Self-consistent Renormalized Quasiparticle Random Phase Approximation (SRQRPA) Method



- i) CD-Bonn potential, $g_A = 1.25$ (solid lines) and $g_A = 1$ (dashed lines) (upper left panel); ii) CD-Bonn (solid lines) and Argonne (dashed lines) potentials with $g_A = 1.25$ (upper right panel); iii) CD-Bonn (solid lines) and Argonne (dashed lines) potentials with $g_A = 1.0$ (lower left panel); iv) Argonne potential with $g_A = 1.25$ (solid lines) and $g_A = 1$ (dashed lines) (lower right panel).

Comments

- If the $T_{1/2}^{0\nu}$ of one of the three nuclei ^{76}Ge , ^{100}Mo or ^{130}Te will be observed, the positivity condition, i.e. $|\eta_k^{LNV}| \geq 0$, constrains the other two to lie in specific intervals, determined by the measured half-life and the relevant NMEs and phase-space factors. This feature is common to all cases of two non-interfering mechanisms generating the $\beta\beta0\nu$ -decay.
- The intervals of T_2/T_1 depend on the type of the two non-interfering mechanisms. However, the differences in the cases of the exchange of heavy Majorana neutrinos coupled to (V+A) currents and i) light Majorana neutrino exchange, or ii) the gluino exchange mechanism, are extremely small for the isotopes considered.
- **if it will be possible to rule out one of these mechanisms as the cause of $\beta\beta0\nu$ decay, most likely one will be able to rule out all three of them (the NMEs are too similar).**

Degeneracies of NMEs

Important feature of the **NMEs** considered within the Self-consistent Renormalized Quasiparticle Random Phase Approximation (SRQRPA) Method: they **differ relatively little!**

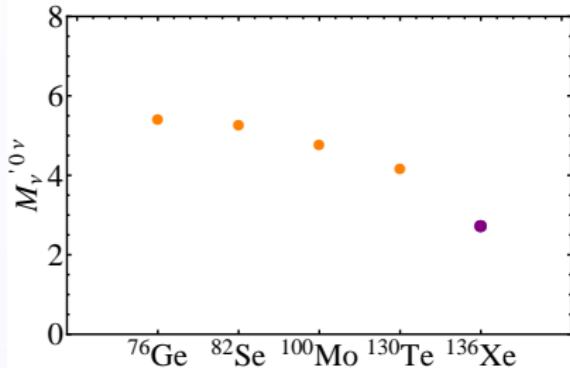
$$|M_{i\kappa} - M_{j\kappa}| \ll M_{i\kappa}, M_{j\kappa}$$

$$\frac{|M_{i\kappa} - M_{j,\kappa}|}{(0.5(M_{i\kappa} + M_{j,\kappa}))} \sim 10^{-2} - 10^{-3}$$

$$i \neq j = {}^{76}\text{Ge}, {}^{82}\text{Se}, {}^{100}\text{Mo}, {}^{130}\text{Te}$$

$$\frac{|M_{i\kappa} - M_{j,\kappa}|}{(0.5(M_{i\kappa} + M_{j,\kappa}))} \sim 10^{-1}$$

$$i = {}^{76}\text{Ge}, \quad j = {}^{136}\text{Xe}$$



NMEs provided using the SRQRPA approach (Simkovic et al.)

EXO Collaboration ArXiv 1205.5608

$$T_{1/2}^{0\nu}({}^{136}\text{Xe}) \geq 1.6 \times 10^{25} \text{y}$$

Using the EXO Limit in the case of two non interfering mechanisms

Positive solutions only if:

$$\frac{T_1 G_1 |M'^{0\nu}_{1,B}|^2}{G_2 |M'^{0\nu}_{2,B}|^2} \leq T_2 \leq \frac{T_1 G_1 |M'^{0\nu}_{1,A}|^2}{G_2 |M'^{0\nu}_{2,A}|^2},$$

The inequality can be enforced if e.g $T_1 > T_{min}$:

$$T_2 \geq \frac{G_1}{G_2} \frac{|M'^{0\nu}_{1,B}|^2}{|M'^{0\nu}_{2,B}|^2} T_{min}$$

For example: $T_{1/2}^{0\nu}(^{136}\text{Xe}) \equiv T_1 > 1.6 \times 10^{25} \text{yr}$ and $T_{1/2}^{0\nu}(^{76}\text{Ge}) \equiv T_2$

we use standard ν and RH Heavy N exchange:

Argonne Potential $g_A=1.25$ (1.0) $T_{1/2}^{0\nu}(^{76}\text{Ge}) > 3.03 \text{ (2.95)} \text{yr}$

Cd-Bonn Potential $g_A=1.25$ (1.0) $T_{1/2}^{0\nu}(^{76}\text{Ge}) > 2.08 \text{ (1.9)} \text{yr}$

Using the EXO Limit in the case of two non interfering mechanisms

Light standard and RH heavy Neutrino

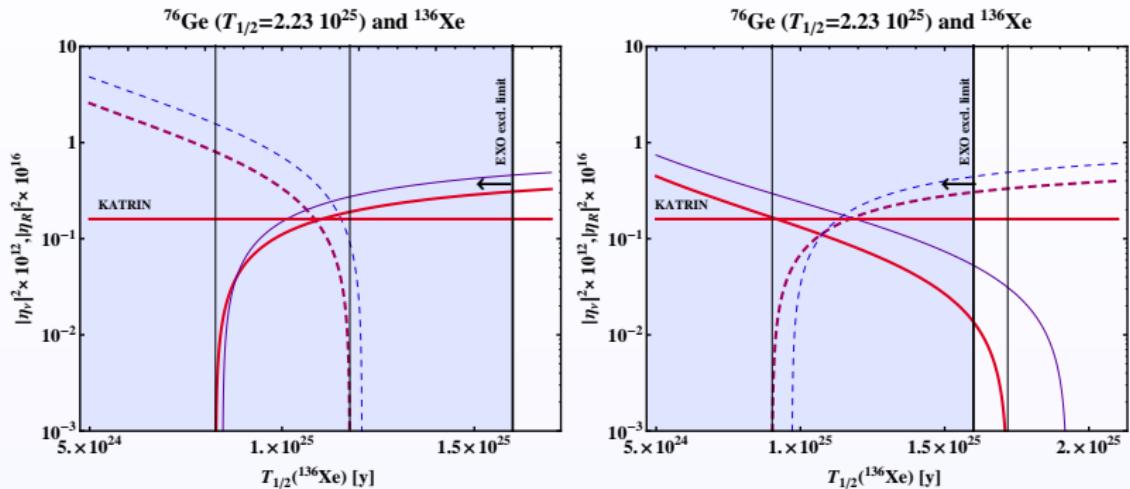


Figure: The values of the rescaled parameters $|\eta_\nu|^2$ (solid lines) and $|\eta_R|^2$ (dashed lines) using $T_{1/2}^{0\nu}({}^{76}\text{Ge})$ and $T_{1/2}^{0\nu}({}^{136}\text{Xe})$ and fixing $T_{1/2}^{0\nu}({}^{76}\text{Ge}) = 2.23 \times 10^{25}$. The solutions using Argonne (left panel) and Cd-Bonn (right panel) Potential are shown in the case of $g_A = 1.25$ (thick lines) and $g_A = 1$ (thin lines).

Possible discrimination of different couple of mechanisms

Using the Argonne Potential to determine the NMEs with $g_A = 1.25(1.0)$ one gets:

- standard light neutrino exchange and the heavy RH Majorana neutrino exchange:

$$1.90 \text{ (1.85)} \leq \frac{T_{1/2}^{0\nu}(^{76}\text{Ge})}{T_{1/2}^{0\nu}(^{136}\text{Xe})} \leq 2.70 \text{ (2.64)}$$

- heavy right-handed Majorana neutrino exchange and the gluino exchange:

$$2.70 \text{ (2.64)} \leq \frac{T_{1/2}^{0\nu}(^{76}\text{Ge})}{T_{1/2}^{0\nu}(^{136}\text{Xe})} \leq 2.78 \text{ (2.67)}$$

Possible discrimination of different couple of mechanisms

Using the [Cd-Bonn Potential](#) to determine the NMEs with $g_A = 1.25(1.0)$ one gets:

- standard light neutrino exchange and the heavy RH Majorana neutrino exchange:

$$1.30 \text{ (1.16)} \leq \frac{T_{1/2}^{0\nu}(^{76}\text{Ge})}{T_{1/2}^{0\nu}(^{136}\text{Xe})} \leq 2.47 \text{ (2.30)}$$

- heavy right-handed Majorana neutrino exchange and the gluino exchange:

$$1.30 \text{ (1.16)} \leq \frac{T_{1/2}^{0\nu}(^{76}\text{Ge})}{T_{1/2}^{0\nu}(^{136}\text{Xe})} \leq 4.43 \text{ (4.25)}$$

Possible discrimination of different couple of mechanisms

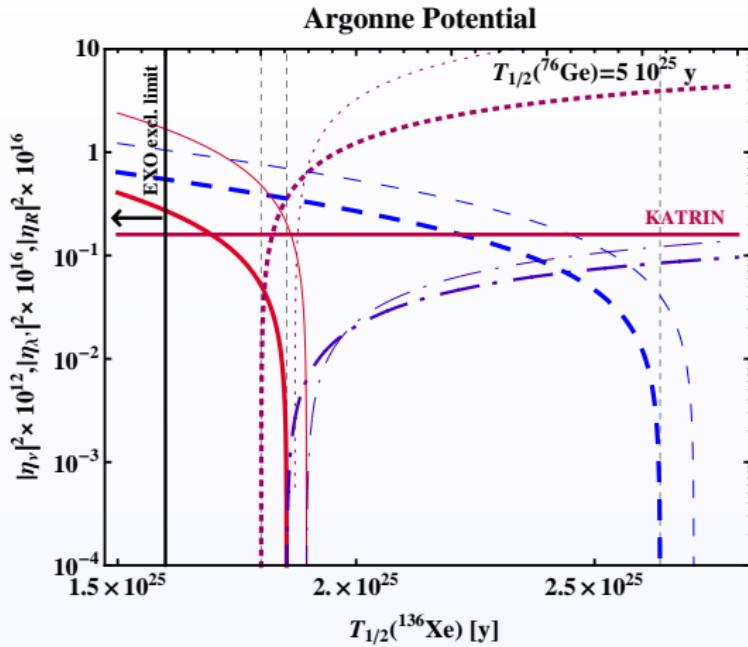


Figure: i) $|\eta_\nu|^2$ and $|\eta_R|^2$ (dot-dashed and dashed lines) and ii) $|\eta_{\lambda'}|^2$ and $|\eta_R|^2$ (solid and dotted lines) The curves are obtained using the sets of NMEs calculated using the Argonne potential.

Possible discrimination of different couple of mechanisms

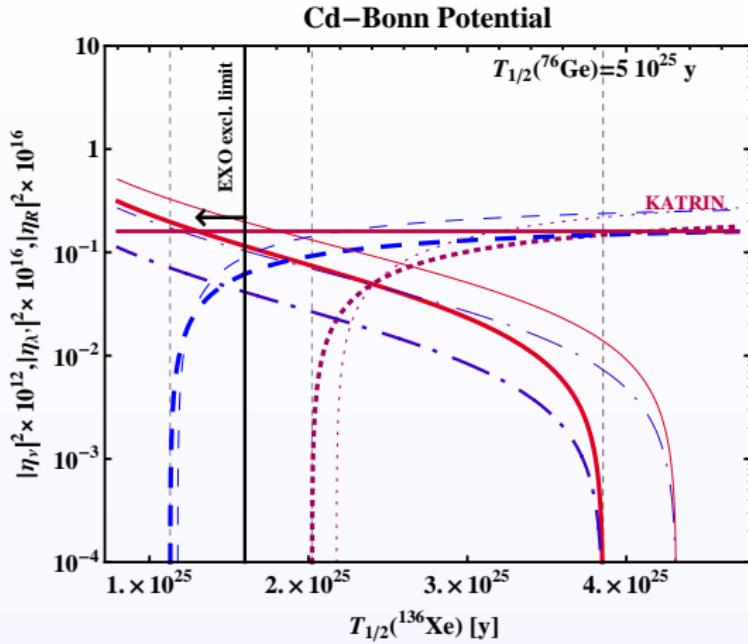


Figure: i) $|\eta_\nu|^2$ and $|\eta_R|^2$ (dot-dashed and dashed lines) and ii) $|\eta_{\lambda'}|^2$ and $|\eta_R|^2$ (solid and dotted lines) The curves are obtained using the sets of NMEs calculated using the Cd–Bonn potential.

Multiple mechanisms: Interfering mechanisms

Example

Example: light Majorana neutrino and gluino exchange mechanisms

$$[T_{1/2,i}^{0\nu} G_i^{0\nu}(E, Z)]^{-1} = |\eta_\nu|^2 (M'^{0\nu}_{i,\nu})^2 + |\eta_{\lambda'}|^2 (M'^{0\nu}_{i,\lambda'})^2 + 2 \cos \alpha M'^{0\nu}_{i,\lambda'} M'^{0\nu}_{i,\nu} |\eta_\nu| |\eta_{\lambda'}|.$$

$$|\eta_\nu|^2 = \frac{D_1}{D}, \quad |\eta_{\lambda'}|^2 = \frac{D_2}{D}, \quad z \equiv 2 \cos \alpha |\eta_\nu| |\eta_{\lambda'}| = \frac{D_3}{D},$$

$$D = \begin{vmatrix} (M'^{0\nu}_{1,\nu})^2 & (M'^{0\nu}_{1,\lambda'})^2 & M'^{0\nu}_{1,\lambda'} M'^{0\nu}_{1,\nu} \\ (M'^{0\nu}_{2,\nu})^2 & (M'^{0\nu}_{2,\lambda'})^2 & M'^{0\nu}_{2,\lambda'} M'^{0\nu}_{2,\nu} \\ (M'^{0\nu}_{3,\nu})^2 & (M'^{0\nu}_{3,\lambda'})^2 & M'^{0\nu}_{3,\lambda'} M'^{0\nu}_{3,\nu} \end{vmatrix}, \quad \text{etc.}$$

Positivity conditions:

$$|\eta_\nu|^2 > 0 \quad |\eta_{\lambda'}|^2 > 0$$

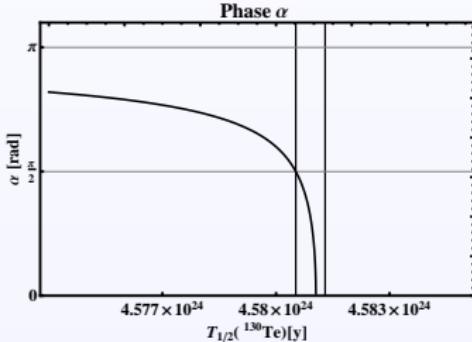
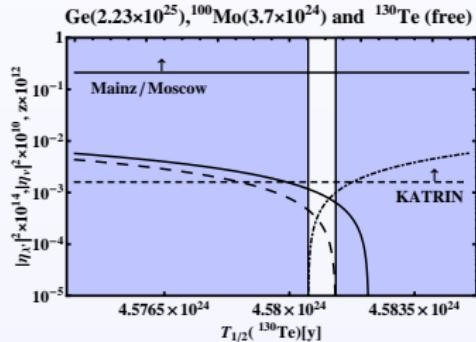
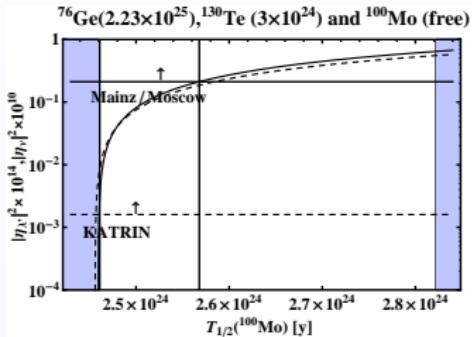
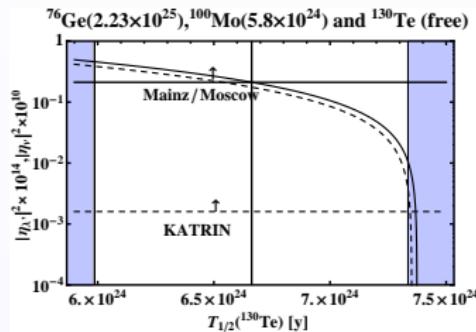
$$-2|\eta_\nu||\eta_{\lambda'}| \leq 2 \cos \alpha |\eta_\nu| |\eta_{\lambda'}| \leq 2|\eta_\nu||\eta_{\lambda'}|$$

Multiple mechanisms: two interfering mechanisms

Results

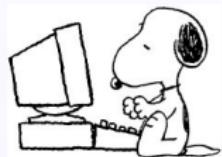
Comment: in most of the cases analyzed destructive interference was found.

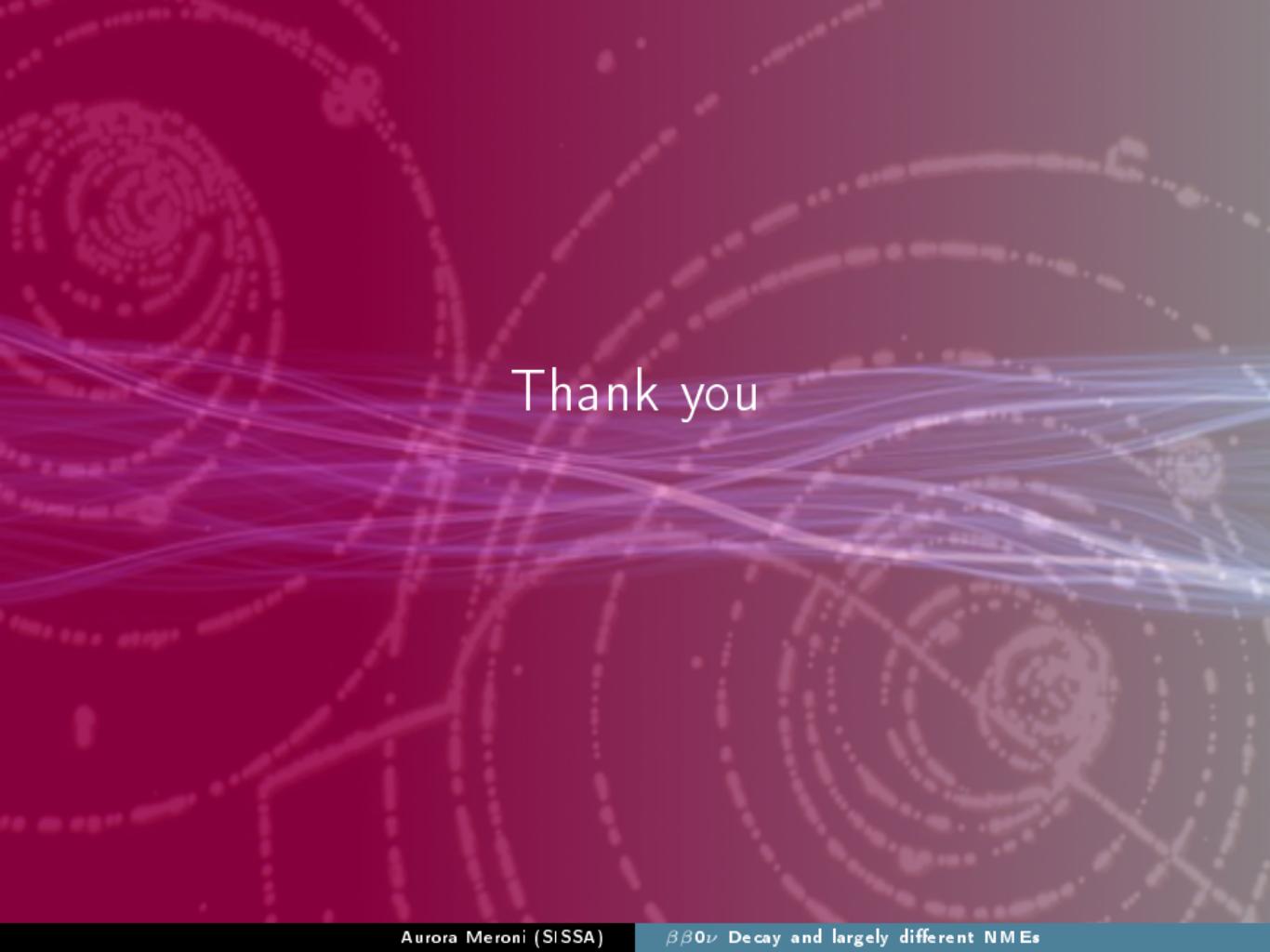
$|\eta_\nu|^2 \times 10^{10}$ (thick line), $|\eta_{\lambda'}|^2 \times 10^{14}$ (dashed line) and $z = 2 \cos \alpha |\eta_\nu| |\eta_{\lambda'}| \times 10^{12}$ (dot-dashed line).



Multiple mechanisms: Summary and Outlook

- If we will observe $\beta\beta0\nu$ decay we must understand which mechanism(s) trigger the decay and if they interfere or not.
- If taking into account all relevant uncertainties, experimental data lie outside the interval of physical solutions $\Rightarrow \beta\beta0\nu$ decay is not generated by the two mechanisms considered.
- The method considered by us can be generalized to the case of more than two $\beta\beta0\nu$ -decay mechanisms.
- It allows to treat the cases of CP conserving and CP nonconserving couplings generating the $\beta\beta0\nu$ -decay in a unique way.
- Isotopes with largely different NMEs can possibly allow to discriminate among different mechanisms (Details in JHEP02(2013)025)





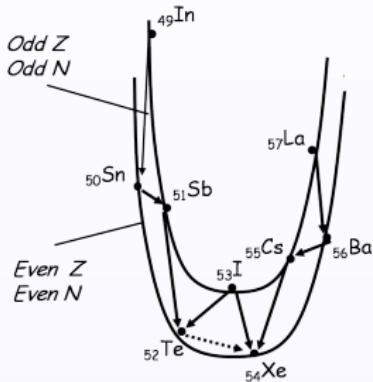
Thank you

Back up slides

$\beta\beta0\nu$ Decay

$$\beta\beta0\nu : (A, Z) \rightarrow (A, Z + 2) + 2e^-$$

- Process forbidden in the SM
- Possible only if neutrinos are Majorana type
- Total Lepton number not conserved $\Delta L = \pm 2$
- Second order in weak coupling constant of the SM



$\beta\beta0\nu$ experiments:

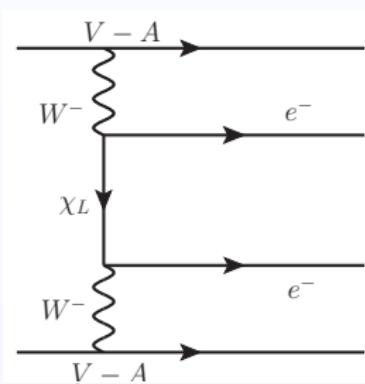
Important bounds already obtained by IGEX (^{76}Ge), CUORICINO (^{130}Te), NEMO3 (^{100}Mo) and H-Moscow experiment (^{76}Ge); **future experiments with sensitivity of $|\langle m \rangle| \sim (0.01 - 0.05) \text{ eV}$:** GERDA (^{76}Ge), CUORE (^{130}Te), EXO (^{136}Xe), KamLAND-Zen (^{136}Xe), SNO+ (^{150}Nd), and many others...

The standard mechanism: Light Majorana neutrino exchange

$\beta\beta0\nu$ -Decay contribution comes from the standard $\mathcal{L}^{CC}(V - A)$ weak interaction

$$Tr[(\bar{e}_L \gamma_\alpha \nu_{eL})(\bar{e}_L \gamma_\beta \nu_{eL})] \propto \sum_k \xi_k m_k (U_{ek})^2$$

- One can define a LNV parameter $\eta_\nu = \frac{\langle m \rangle}{m_e}$



$$\langle m \rangle = \left| \sum_j^{\text{light}} \left(U_{ej}^{\text{PMNS}} \right)^2 m_j \right|, \text{ (all light } m_j \geq 0 \text{)} ,$$

- U is **CP-violating**, in general:

$$(U_{ej})^2 = |U_{ej}|^2 e^{i\alpha_j}, \quad j = 1, 2, 3$$

α_{21}, α_{31} - **Majorana CPV phases**.

- the leptonic chiral structure is **S+PS**:

$$\mathcal{M} \propto \langle m \rangle [\bar{e}(1 + \gamma_5)e^c] A_{\alpha\beta}^{\text{h.current}}$$

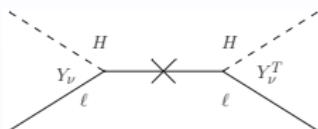
Heavy Majorana Neutrino Exchange with $M_k \gtrsim 10$ GeV

RH Neutrinos and See-saw mechanisms

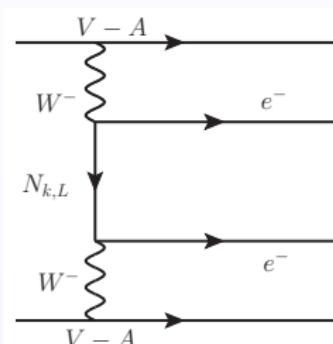
3 RH $N_R \sim (1, 0)$ N_k with masses

$M_k \gtrsim 10$ GeV i.e. $M_k \gg 100$ MeV

(typical energy scale of the $\beta\beta 0\nu$ -decay)



$$\mathcal{L}_{Y+M} = -(Y_\nu)_{jl}(\bar{\ell}_L \tilde{H})_j N_{IR} - \frac{1}{2} \overline{(N_{IR})^c} (M^N)_{II'} N_{I'R} + h.c.$$



V-A coupling: The LNV parameter is:

$$\eta_N^L = \sum_k^{\text{heavy}} U_{ek}^2 \frac{m_p}{M_k},$$

m_p = proton mass,
 U_{ek} is the mixing matrix due to $V - A$ coupling.

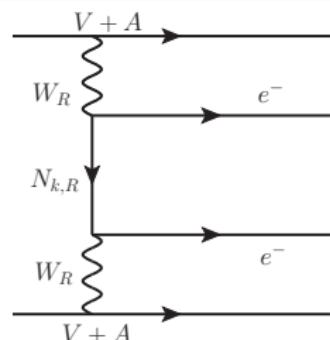
$$\eta_N^L [\bar{e}(1 + \gamma_5)e^c]$$

RH Heavy Majorana neutrino exchange with $M_k \gtrsim 10$ GeV

V+A coupling in the CC current

$$SU(2)_L \otimes SU(2)_R$$

$$\mathcal{L}_{\text{weak}} \supset (\bar{e} \gamma_\alpha (1 + \gamma_5) \nu_{eR}) W_{\mu R}^-$$



$$\eta_N^R [\bar{e}(1 - \gamma_5)e]$$

where $\nu_{eR} = \sum_k V_{ek} N_{kR}$, $C \bar{N}_k^T = \xi N_k$.

The LNV parameter is:

$$\eta_N^R = \left(\frac{M_W}{M_{WR}} \right)^4 \sum_k^{\text{heavy}} V_{ek}^2 \frac{m_p}{M_k}.$$

$$M_{W_R} \gtrsim 2.5 \text{ TeV}.$$

Here V_{ek} is the mixing matrix by which N_k couple to the electron in the $(V + A)$ charged lepton current.

SUSY with R_p and $\beta\beta 0\nu$ Decay I

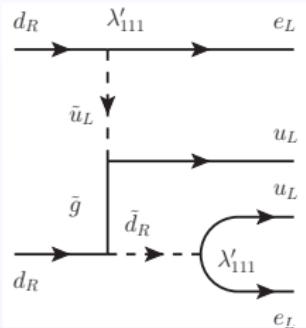
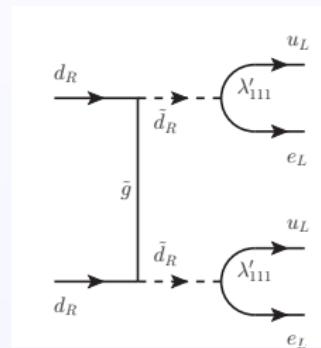
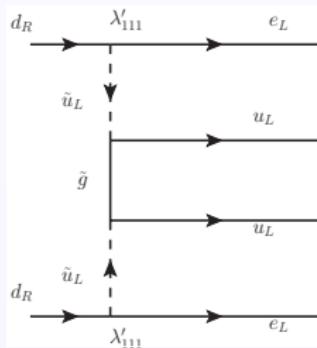
Short Range Mechanisms

The LNV λ' -couplings is given by in the **R-parity breaking part of the superpotential**:

$$\mathcal{L}_{R_p} = \lambda'_{111} \left[(\bar{u}_L \ \bar{d}_L) \begin{pmatrix} e_R^c \\ -\nu_{eR}^c \end{pmatrix} \tilde{d}_R + (\bar{e}_L \ \bar{\nu}_{eL}) d_R \begin{pmatrix} \tilde{u}_L^* \\ -\tilde{d}_L^* \end{pmatrix} + (\bar{u}_L \ \bar{d}_L) d_R \begin{pmatrix} \tilde{e}_L^* \\ -\tilde{\nu}_{eL}^* \end{pmatrix} + h.c. \right]$$

Assuming the **dominance of the gluino exchange** the LNV parameter is:

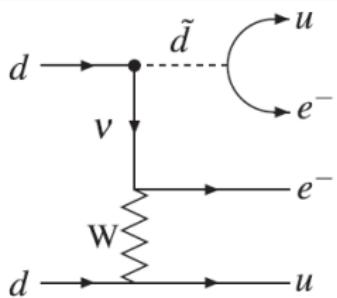
$$\eta_{\lambda'} \sim \frac{\pi \alpha_s}{m_{\tilde{g}}} \frac{\lambda'_{111}^2}{m_{\tilde{f}}^4}, \quad \alpha_s = \frac{g_3^2}{4\pi}$$



Hirsch, K.-Kleingrothaus, Kovalenko Phys. Rev. Lett. 75 (1995)
Phys. Rev. D 53 (1996)

SUSY with R_p and $\beta\beta 0\nu$ Decay II

Long Range Mechanisms



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- The mixing between the scalar superpartners $\tilde{q}_{L,R}$ of the left and right handed quarks $q_{L,R}$ plays a crucial role.
- The squark-gluino mechanisms is due to the **non-diagonality of the squark mass matrix**.
- \tilde{q}_L and \tilde{q}_R are superpositions of mass eigenstates with a given mixing angle $\theta_{(k)}^d$

$$\eta_{\tilde{q}} \sim \sum_k \frac{\lambda'_{11k} \lambda'_{1k1}}{G_F m_{\tilde{d}_{(k)}}} \sin(2\theta_{(k)}^d)$$

$\eta_{\tilde{q}} \neq 0$ if m_i of light neutrinos is zero but it is zero if $\theta_{(k)}^d = 0$

Nuclear Matrix Elements

Nuclear transition	$G^{0\nu}(E_0, Z)$ [y^{-1}]	$ M'^{0\nu}_\nu $				$ M'^{0\nu}_N $				$ M'^{0\nu}_{\lambda'} $				$ M'^{0\nu}_{\tilde{q}} $			
		NN pot.	m.s.	$g_A =$	1.0	1.25	$g_A =$	1.0	1.25	$g_A =$	1.0	1.25	$g_A =$	1.0	1.25	$g_A =$	1.0
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	$7.98 \cdot 10^{-15}$	Argonne	intm.	3.85	4.75	172.2	232.8	387.3	587.2	396.1	594.3						
			large	4.39	5.44	196.4	264.9	461.1	699.6	476.2	717.8						
		CD-Bonn	intm.	4.15	5.11	269.4	351.1	339.7	514.6	408.1	611.7						
			large	4.69	5.82	317.3	411.5	392.8	595.6	482.7	727.6						
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	$3.53 \cdot 10^{-14}$	Argonne	intm.	3.59	4.54	164.8	225.7	374.5	574.2	379.3	577.9						
			large	4.18	5.29	193.1	262.9	454.9	697.7	465.1	710.2						
		CD-Bonn	intm.	3.86	4.88	258.7	340.4	328.7	503.7	390.4	594.5						
			large	4.48	5.66	312.4	408.4	388.0	594.4	471.8	719.9						
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	$5.73 \cdot 10^{-14}$	Argonne	intm.	3.62	4.39	184.9	249.8	412.0	629.4	405.1	612.1						
			large	3.91	4.79	191.8	259.8	450.4	690.3	449.0	682.6						
		CD-Bonn	intm.	3.96	4.81	298.6	388.4	356.3	543.7	415.9	627.9						
			large	4.20	5.15	310.5	404.3	384.4	588.6	454.8	690.5						
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	$5.54 \cdot 10^{-14}$	Argonne	intm.	3.29	4.16	171.6	234.1	385.1	595.2	382.2	588.9						
			large	3.34	4.18	176.5	239.7	405.5	626.0	403.1	620.4						
		CD-Bonn	intm.	3.64	4.62	276.8	364.3	335.8	518.8	396.8	611.1						
			large	3.74	4.70	293.8	384.5	350.1	540.3	416.3	640.7						

The NMEs were obtained within the Self-consistent Renormalized Quasiparticle Random Phase Approximation (SRQRPA). From Faessler, Simkovic